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13. ABSTRACT (MAX 200 WORDS): THE MAGNETO-MECHANICAL BEHAVIOUR OF FIVE STEELS, MILD STEEL, HSLA 80, HY 100 AND A QUENCHED ALLOY STEEL, HAS BEEN INVESTIGATED. MAGNETIC FIELDS OF THE ORDER OF THE EARTH'S FIELD AND COMPRESSIVE STRESSES UP TO 200 MPA WERE APPLIED TO THE STEELS. THE INCREASE IN MAGNETIZATION DUE TO STRESS CYCLING IN A CONSTANT APPLIED FIELD AND TO FIELD CYCLING AT ACONSTANT STRESS WERE MEASURED. THE RESULTS SHOW THAT THE DIFFERENTIAL PERMEABILITY OF THE STEEL LARGELY DETERMINES THE MAGNETIZATION INCREASE AND THAT STEELS AND SIMILAR MICROSTRUCTURES HAVE SIMILAR MAGNETO-MECHANICAL RESPONSE. THE STRENGTH OR HARDNESS OF THE STEEL IS A LESS RELIABLE INDICATOR OF MAGNETO-MECHANICAL RESPONSE.

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EFFECT OF STEEL METALLURGY ON ITS MAGNETO-MECHANICAL BEHAVIOUR IN WEAK MAGNETIC FIELDS

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Abstract—The magneto-mechanical behaviour of five steels, mild steel, HSLA 80, HY 80, HY 100 and a quenched alloy steel, has been investigated. Magnetic fields of the order of the Earth's field and compressive stresses up to 200 MPa were applied to the steels. The increase in magnetization due to stress cycling in a constant applied field and to field cycling at constant stress was measured. The results show that the differential permeability of the steel largely determines the magnetization increase and that steels with similar microstructures have similar magneto-mechanical response. The strength or hardness of the steel is a less reliable indicator of magneto-mechanical response.

1. INTRODUCTION

The magnetization of a ferromagnet in an applied magnetic field can be drastically modified by the application of stress [1]. This phenomenon is known as the magneto-mechanical effect and has come under renewed scrutiny in recent years because of the possibility of measuring stress in steel structures using magnetic methods. One difficulty in achieving this goal is that the composition, heat treatment and microstructure of the steel have an effect on its magneto-mechanical behaviour, so that a measuring instrument would need to be calibrated for each steel.

A review of the literature revealed that investigations of the magneto-mechanical effect have been restricted to a fairly narrow range of materials [2]. There are few direct comparisons of different materials. Irons and mild steels have received most attention [1, 3–8]. More highly-alloyed steels which have been examined include a 3% nickel steel [9], St5 0.3% carbon steel [10–12], U8 0.8% carbon tool steel [13], QT35 alloy plate steel [4], 1 and 2% manganese pipeline steels [14–17], SAE 4340 alloy steel [18] and ferritic and martensitic stainless steels [18, 19]. Other steels have been unidentified [20] or characterized only in terms of hardness or coercivity [21, 22].

Almost all studies have concerned one-dimensional geometry, but some work has been carried out for two-dimensional situations [8, 23, 24]. Here "one-dimensional" means that stress, applied field and magnetic induction are coaxial.

In the present work, results are reported for five different steels with a range of strength levels and metallurgical structures. There are three main aspects of the work:

(i) Investigation of the effects of cyclic compressive stress on the magnetization of steel in a weak field similar to the Earth's magnetic field.

(ii) Investigation of the possibility of measuring a constant stress by applying a weak, cyclic magnetic field and measuring the resultant magnetization change.

(iii) Investigation of the effects of steel metallurgy on aspects (i) and (ii).

2. MATERIALS AND METHODS

The main interest of the present work was in the alloy plate steels HSLA 80 (optimized ASTM A710 Grade A), HY 80 and HY 100 in their standard heat-treated conditions. Two other steels, a mild steel and a quenched alloy steel, were included in order to increase the range of magnetic and mechanical properties.

HSLA 80 is a copper precipitation hardened steel with a nominal yield strength of 550 MPa (80 ksi). The microstructure consists of ferrite with small islands of secondary transformation products [25]. The HY steels are quenched and tempered to achieve their nominal yield strengths of 550 and 690 MPa. The compositions (wt%) of the specimens used in the present study are as follows:

	C	Si	Mn	Ni	Cr	Mo	Cu
HSLA 80	0.06	0.29	1.41	0.80	0.01	0.01	0.98
HY 80	0.12	0.17	0.16	2.85	1.32	0.50	0.03
HY 100	0.15	0.28	0.27	3.02	1.49	0.50	0.03

Cylindrical specimens of HSLA 80, HY 80 and HY 100 were prepared from the as-received plate by turning to slightly oversized diameter, stress relieving at 550°C for 1 h and centreless grinding to final diameter. The mild steel (MS) specimens were machined directly from bar stock without stress relief. They have a ferrite–pearlite microstructure. The quenched alloy steel (designated "Q") was water quenched from 915°C to a martensitic microstructure and ground to final size. It did not receive a temper or stress relief and therefore had a very high hardness compared with the other steels. The Vickers hardnesses of the specimens are as follows:

MS	147 HV_{30}
HSLA 80	210
HY 80	225
HY 100	275
Q	365

Magnetic measurements were carried out using the magnetic circuit shown in Fig. 1. This consists of two rods of the steel under test (10.2 mm diameter by 210 mm) joined by two soft iron yokes in an arrangement similar to that used by Lliboutry [21]. Coils for applying the magnetic field (H coils) and for measuring the change in magnetic induction (B coils) are wound on formers into which the rods are inserted. A simple electronic integrator circuit was used to integrate the e.m.f. induced in the B coils to give a reading of the magnetic induction in the circuit.

Stress was applied by directly loading the steel specimens in compression along their axes. Thus, stress (σ), applied field (H), and magnetic induction (B) are coaxial. Fields up to 200 A/m and stresses up to 200 MPa were applied, after initially demagnetizing the specimens.

Two types of magnetic process were investigated, in which either the stress was varied in a constant applied field, or the field was varied under constant stress. These processes have been designated as follows:

(i) $DH(\sigma\bar{\sigma})^n$ in which the specimen is demagnetized (D), magnetic field applied (H), and stress applied (σ) and removed ($\bar{\sigma}$) n times. Unless otherwise stated, results are for $\sigma = -200$ MPa.

(ii) $D\sigma h_{\sim}$ in which the specimen is demagnetized, stress applied and the magnetic field cycled between $+h$ and $-h$.

The magnetic fields applied to the specimens were similar in magnitude to the earth's field. The earth's field itself has essentially no effect on the magnetization of the specimens in the magnetic test circuit. The component of the earth's field transverse to the specimen axis has little effect because of the demagnetization factor associated with the shape of the specimens. The longitudinal component of the earth's field has opposite effects in each of the two specimens in the circuit and therefore is cancelled out.

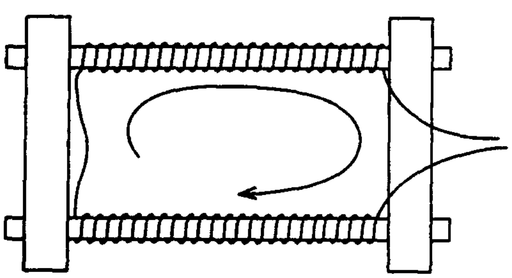

Fig. 1. Schematic diagram of the magnetic circuit.

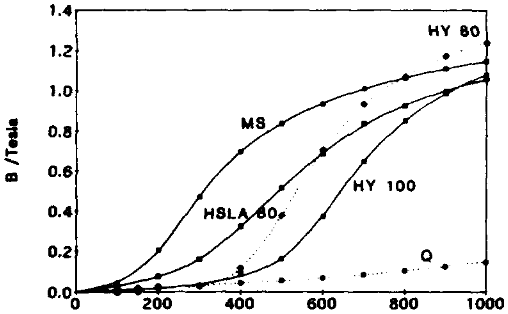

Fig. 2. Normal induction curves for MS -●-, HSLA 80 -■-, HY 80 ·◆·, HY 100 -•-, and Q ··●··.

3. RESULTS

3.1. Normal induction

The normal induction curves which were measured for the five steels (magnetic process DH) are shown in Fig. 2. At the higher field strengths these should be regarded as a comparison rather than an absolute measurement of the induction because of the nature of the magnetic circuit. As expected from the mechanical hardness of the specimens, the approximate order of increasing magnetic hardness is MS, HSLA 80, HY 80, HY 100 and Q. The initial permeabilities, μ_i, and relative initial permeabilities, μ_r, of the specimens are as follows:

MS	0.24 mT/Am^{-1}	191
HSLA 80	0.19	151
HY 80	0.100	80
HY 100	0.091	72
Q	0.086	68

3.2. Process $DH(\sigma\bar{\sigma})^n$

A typical response to the process $DH(\sigma\bar{\sigma})^n$ is shown in Fig. 3. After the first one or two stress cycles the

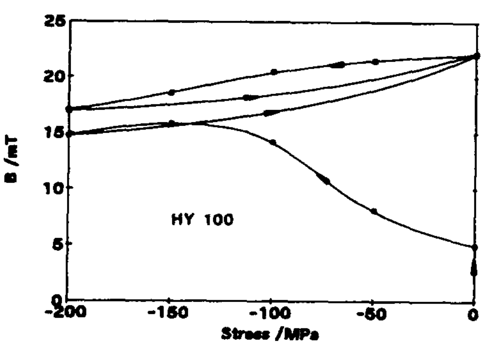

Fig. 3. Changes in induction during the process $DH(\sigma\bar{\sigma})^2$ for HY 100 steel with $H = 50$ A/m and $\sigma = -200$ MPa (average of $|\Delta B|$ for fields of 50 and -50 A/m).

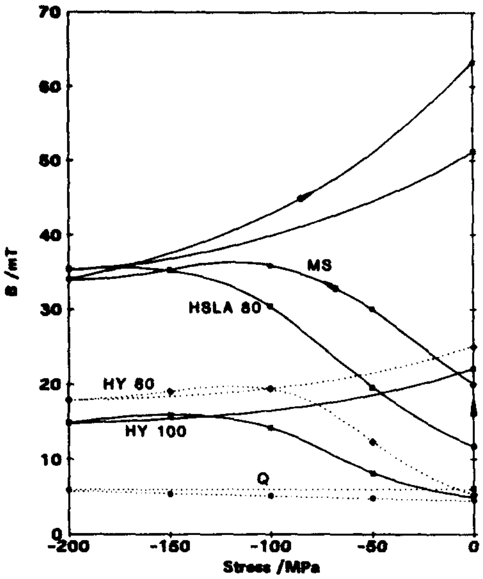

Fig. 4. As for Fig. 3 but showing results for the first cycle $DH\sigma\bar{\sigma}$ for all five steels.

induction follows a (nearly) stable hysteresis loop, and it is then possible to identify reversible and irreversible components of the change in induction due to stress cycling [10, 17]. The reversible component, ΔB^r, is the difference in induction between the tips of the stable loop, $DH(\sigma\bar{\sigma})^n\sigma - DH(\sigma\bar{\sigma})^n$. The irreversible component, ΔB^i, is the induction at zero stress relative to that before the application of stress, $DH(\sigma\bar{\sigma})^n - DH$. It is usually found that ΔB^i moves the induction towards the anhysteretic (equilibrium) induction and that ΔB^r is governed by the thermodynamic relation

$$\left(\frac{\partial B}{\partial \sigma}\right)_H = \left(\frac{\partial \lambda}{\partial H}\right)_\sigma \quad (1)$$

where λ is the magnetostriction [2].

The response of the five steels to the process $DH\sigma\bar{\sigma}$ with field of 50 A/m is compared in Fig. 4. On the basis of this response, the steels can be classified into three groups:

(i) The magnetically-soft steels MS and HSLA 80 exhibit very large increases in induction due to stress cycling.

(ii) The quenched and tempered HY steels show an intermediate response.

(iii) The magnetically and mechanically hard Q steel manifests only slight susceptibility to stress.

For the weak magnetic fields which were investigated (< 200 A/m), the reversible and irreversible components of the magnetization change in the [illegible])^n process show a linear dependence on the field. This is illustrated in Fig. 5 for HY 100. [illegible] contains the slopes of curves for the different steels such as those drawn in Fig. 5 for HY 100 steel. Note that the differential permeability, μ', is the slope of the normal induction curve DH and increases with increasing applied field, especially for the mild steel specimen.

The two final columns of Table 1 illustrate another difference between the steels. For steel Q, almost all of ΔB^i occurs in the first cycle. However, for the magnetically soft steels, several cycles (8–10) are required before ΔB^i saturates (the induction continues to creep upw[illegible]g the initial cycles). For the HY steels, ΔB^i s[illegible]bout three cycles. The increment in indu[illegible] a[illegible]he completion of each cycle decays monotonic[illegible] [7].

3.3. Process $D\sigma h$

The schematic response of the st[illegible]s to the $D\sigma h$ magnetic process is depicted in Fig. 6. It is clear that Rayleigh's law does not strictly apply be[illegible]use the first loop differs significantly from later loops. A stable hysteresis loop was followed after the first one or two field cycles for all five steels. Symmetry implies that the stable loop is centred on the B–H origin, so there is no ΔB^i component for this magnetic process. The reversible component of the induction change shown in Fig. 6 serves as a potential indicator of the stress applied to the steel.

The induction after the initial application of the magnetic field ($D\sigma h$) and the component ΔB^r for MS and HY 100 steels are shown in Fig. 7 for a range of applied stresses. The induction after $D\sigma h$ initially increases with increasing compressive stress. The component ΔB^r is approximately linear in the applied stress, decreasing as the compressive stress increases. Table 2 shows that while ΔB^r is useful as an indicator of stress for the magnetically soft steels, it lacks sensitivity in the case of magnetically hard steel.

4. DISCUSSION

4.1. Reversible components

It is clear from Table 1 that the reversible component of the magnetization change in the process $DH(\sigma\bar{\sigma})^n$ is closely related to the differential per-

Table 1. Slopes of B–H curves in mT/Am^{-1} for the process $DH(\sigma\bar{\sigma})^n$ with $\sigma = -200$ MPa

	μ'						
Steel	$H = 0$	$H = 25$	$H = 50$	$H = 100$	$\Delta B^r/H$	$\Delta B^i/H$	$\Delta B_1/H$*
MS	0.24	0.36	0.47	0.60	−0.60	1.11	0.89
HSLA 80	0.19	0.22	0.27	0.31	−0.38	0.91	0.78
HY 80	0.10	0.10	0.12	0.13	−0.13	0.36	0.34
HY 100	0.09	0.10	0.10	0.12	−0.12	0.36	0.35
Q	0.09	0.09	0.09	0.09	−0.004	0.03	0.03

*$\Delta B_1/H$ is the slope of the line for the increase in induction after the first stress cycle $DH\sigma\bar{\sigma} - DH$.

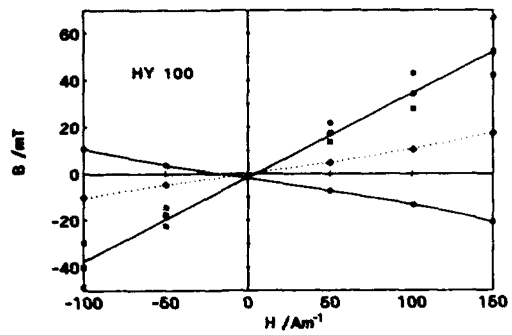

Fig. 5. Changes in induction in HY 100 steel in the process $DH(\sigma\bar{\sigma})^n$ with $\sigma = -200$ MPa. Normal induction curve DH ··◆··, ΔB^r –●–, ΔB^i –■–, $DH\sigma\bar{\sigma}$ ●, and $DH\sigma$ (with $\sigma = -100$ MPa) *.

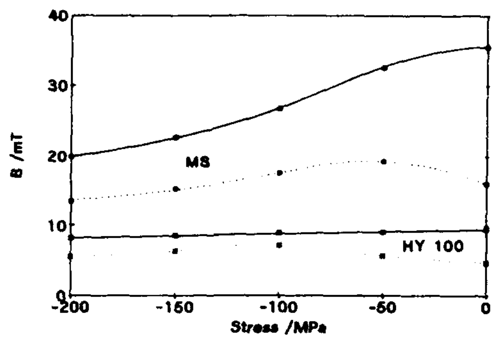

Fig. 7. The induction after the process $D\sigma h$ ····, and the reversible component of the induction in the process $D\sigma h_{\smile}$ ——, for MS (●) and HY 100 (*) with $h = 50$ A/m.

meability of the steel. This arises because at low field strengths the induction (B) and the magnetostriction (λ) have similar dependence on the applied field (H). Therefore, from equation (1)

$$\Delta B^r \doteqdot \left(\frac{\partial \lambda}{\partial H}\right)\Delta\sigma \doteqdot f\left(\frac{\partial B}{\partial H}\right)\Delta\sigma = f\mu'\,\Delta\sigma \qquad (2)$$

where f is a proportionality factor approximately equal to 0.5 A/m MPa for the steels which were examined. The only exception is steel Q which has a very small ΔB^r, possibly because the steel was not stress relieved and therefore retained high internal stresses. The response of the steel to external applied stress was therefore diminished.

For the process $D\sigma h_{\smile}$ with small field amplitude h, the reversible component of the induction change can be derived from Rayleigh's law [26]

$$B = \mu_i H + \nu H^2 \qquad (3)$$

where μ_i is the initial permeability and ν is the Rayleigh coefficient. The reversible component for the $D\sigma h_{\smile}$ process is then

$$\Delta B^r = 2(\mu_i h + \nu h^2) \qquad (4)$$

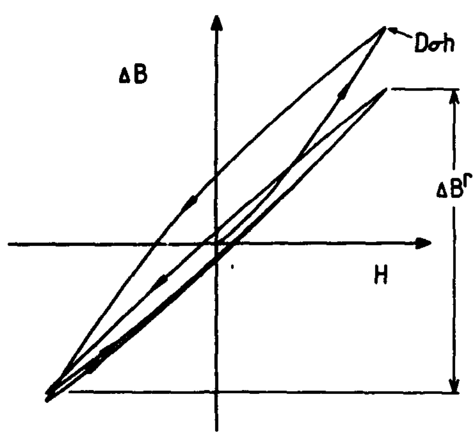

Fig. 6. Schematic response to the $D\sigma h_{\smile}$ process for field amplitudes up to 50 A/m and stresses up to 200 MPa in compression.

where both μ_i and ν may be stress dependent. The values of μ_i and ν are shown in Table 3. The initial permeability was obtained from the initial slope of the induction curve ($D\sigma h$). The Rayleigh coefficients were obtained from the difference in induction between the ascending and descending branches of the stable hysteresis loop (during $D\sigma h_{\smile}$) at zero applied field (equal to νh^2 according to Rayleigh's law). The values shown in Table 3 are the averages of the results obtained for field amplitudes of 25 and 50 A/m.

For most of the steels, compressive stress initially causes a slight increase in the initial permeability but μ_i decreases for larger compressive stresses. The coefficient shows a steady decline with increasing compressive stress. The steels examined by Lliboutry also displayed this behaviour, suggesting that all steels behave in a similar way [21].

4.2. Irreversible component

Table 1 shows that ΔB^i in the process $DH(\sigma\bar{\sigma})^n$ is also related to the differential permeability of the steel (except for steel Q). It is expected that the anhysteretic induction is the upper limit of that achievable in the $DH(\sigma\bar{\sigma})^n$ process, but for the values of H and σ which were used, this limit is not approached for any of the steels in the present investigation.

4.3. Steel metallurgy

The reversible and irreversible components of the magnetization change during the processes investi-

Table 2. Effect of stress on ΔB^r in the process $D\sigma h_{\smile}$

Steel	h/Am^{-1}	ΔB^r/mT $\sigma = 0$	$\sigma = -200$ MPa	$\Delta B^r(-200)/\Delta B^r(0)$
MS	25	17.2	8.5	0.49
	50	35.5	20.0	0.56
HSLA 80	25	10.3	6.6	0.64
	50	22.0	13.5	0.61
HY 80	25	4.9	4.0	0.82
	50	10.6	8.4	0.79
HY 100	25	4.6	4.1	0.88
	50	9.5	8.2	0.86
Q	25	—	—	—
	50	8.4	8.2	0.97
	100	18.0	17.1	0.95

Table 3. Values of μ_i in mT/Am^{-1} and ν in μT/(Am^{-1})^2

Stress/MPa	0		−50		−100		−150	
	μ_i	ν	μ_i	ν	μ_i	ν	μ_i	ν
MS	0.24	2.3	0.25	1.6	0.23	1.0	0.20	0.6
HSLA 80	0.19	1.0	0.19	0.7	0.17	0.5	0.13	0.3
HY 80	0.100	0.2	0.098	0.2	0.086	0.2	0.080	0.1
HY 100	0.091	0.2	0.093	0.2	0.088	0.2	0.081	0.1
Q	0.086	0.06	0.089	0.05	0.087	0.05	0.087	0.05

gated in the present work are primarily determined by the differential permeability of the steel. Much more information is available on the effects of steel metallurgy on permeability than direct information about its effects on magneto-mechanical behaviour [1, 27–31].

The mild steel used in the present study contains carbon in the form of cementite in pearlite colonies. It is well known that carbon in this form decreases the permeability of iron. Fine copper particles precipitated in a ferrite matrix (as in HSLA 80) are also known to reduce permeability. The precipitation of copper affects μ_i much earlier in the ageing process than it affects coercivity [28]. The effects of quenching and tempering (of steels similar to HY 80 and HY 100) on permeability are well established [27, 29]. The fine microstructures, high dislocation densities and internal stresses of quenched steels result in low permeability. Although tempering causes the precipitation of cementite, the decrease in permeability due to these particles is more than compensated by a reduction in dislocation density and internal stress.

The same microstructural features also affect the mechanical properties of the steels, so that mechanical and magnetic hardness are correlated to some degree. However, from the results of the present study, it is clear that although the copper precipitation hardening of HSLA 80 produces equivalent mechanical strength to quenched and tempered HY 80, its initial permeability is considerably higher than that of HY 80. Similarly, HY 80 and HY 100 have significantly different strength, but their microstructures, permeabilities and magneto-mechanical behaviour are similar.

The internal stresses of the quenched alloy steel Q result in minimal magnetic response to externally applied stress, in spite of an initial permeability close to that of the HY steels.

5. CONCLUSION

The present work has shown that the magnetization increase resulting from cyclic stressing of a variety of steels in a weak magnetic field is largely determined by the differential permeability of the steel (and the magnitude of the stress). The magnetization change during field cycling under a constant stress depends on the magnitude of the stress, especially for steels with a relatively high differential permeability. Permeability and magneto-mechanical response are similar in steels with similar microstructures, but they are not directly correlated with the mechanical strength of the steel.

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